Kaon Physics at BNL

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The rare kaon decay program at BNL is summarized. A brief review of recent results is provided along with a discussion of prospects for the future of this program. The primary focus is the two golden modes: $K^+ \to \pi^+ \nu\overline{\nu}$ and $K_L^\circ \to \pi^\circ \nu\overline{\nu}$. The first step in an ambitious program to precisely measure both branching ratios has been successfully completed with the observation of two $K^+ \to \pi^+ \nu\overline{\nu}$ events by E787. The E949 experiment is poised to reach an order of magnitude further in sensitivity and to observe ~10 Standard Model events.

1. INTRODUCTION

The AGS has had a broad and rich program in kaon physics. With the recent successful commissioning of the Relativistic Heavy Ion Collider (RHIC), the primary role of the AGS has shifted to become an injector of heavy ions for RHIC. Nevertheless, the AGS remains the highest intensity proton synchrotron in the world and is designed to be available for ~20 hours/day when not filling RHIC, and as such retains an important role in the US high energy physics (HEP) program. DOE and BNL have approved and agreed to fund one new HEP experiment to run at the AGS between RHIC fills: the E949 experiment which seeks to make a precise measurement of the branching ratio $B(K^+ \to \pi^+ \nu\overline{\nu})$.

1.1. $K \to \pi \nu\overline{\nu}$

The kaon physics program at the AGS is centered on the two golden modes: $K^+ \to \pi^+ \nu\overline{\nu}$ and $K_L^\circ \to \pi^\circ \nu\overline{\nu}$. These modes are interesting as there is essentially no theoretical ambiguity in extracting fundamental CKM parameters from measurements of the branching ratios[1,2]. The theoretical uncertainty in $B(K^+ \to \pi^+ \nu\overline{\nu})$ is ~7% and is even smaller in $B(K_L^\circ \to \pi^\circ \nu\overline{\nu})$, only ~2%; in both cases the hadronic matrix element is extracted from the $K^+ \to \pi^\circ e^+ \nu_e$ (K_{e3}) decay rate.

The unitarity of the CKM matrix can be expressed as

$$V_{us}^* V_{ud} + V_{cs}^* V_{cd} + V_{ts}^* V_{td} = \lambda_u + \lambda_c + \lambda_t = 0$$

with the three vectors $\lambda_i \equiv V_{is}^* V_{id}$ converging to form a very elongated triangle in the complex plane. The length of first vector $\lambda_u = V_{us}^* V_{ud}$ is precisely determined from K_{e3} decay. The height of the triangle, $Im\lambda_t$, can be measured by $K_L^\circ \to \pi^\circ \nu\overline{\nu}$ and the length of the third side $\lambda_t = V_{ts}^* V_{td}$ is measured by $K^+ \to \pi^+ \nu\overline{\nu}$. Measurements of the two $K \to \pi \nu\overline{\nu}$ modes, along with the well known K_{e3}, will completely determine the unitarity triangle.

Comparison of CKM parameters as measured from the golden $K \to \pi \nu\overline{\nu}$, $B_d^\circ \to \psi K_S^\circ$ and $\Delta M_{B_d}/\Delta M_{B_s}$ modes, provide the best opportunity to over-constrain the unitary triangle and to search for new physics. In particular, comparisons of

- $|V_{td}|$ from $K^+ \to \pi^+ \nu\overline{\nu}$ and from the ratio of the mixing frequencies of B_d and B_s mesons $\Delta M_{B_d}/\Delta M_{B_s}$ [2],
- β from $B(K_L^\circ \to \pi^\circ \nu\overline{\nu})/B(K^+ \to \pi^+ \nu\overline{\nu})$ and from the time dependent asymmetry in the decay $B_d^\circ \to \psi K_S^\circ$ [3,4]

offer outstanding opportunities to explore the Standard Model (SM) picture of CP-violation.

The SM prediction for the $K \to \pi \nu\overline{\nu}$ branching ratios are $B(K^+ \to \pi^+ \nu\overline{\nu}) = (0.75 \pm 0.29) \times 10^{-10}$ and $B(K_L^\circ \to \pi^\circ \nu\overline{\nu}) = (0.26 \pm 0.12) \times 10^{-10}$ [1]. In addition, an upper limit on $B(K^+ \to \pi^+ \nu\overline{\nu})$ can be derived in a theoretically unambiguous way from the current limit on B_s mixing; this limit is $B(K^+ \to \pi^+ \nu\overline{\nu}) < 1.32 \times 10^{-10}$ [5].

2. SUMMARY OF RECENT RESULTS

A large number of new results are available from several recently completed rare kaon decay experiments at BNL (running during 1995–98). There were three experiments running during this period — E787: Search for $K^+ \to \pi^+ \nu\overline{\nu}$; E865: Search for $K^+ \to \pi^+ \mu^+ e^-$ and E871: Search for $K^\circ_L \to \mu e$.

2.1. Lepton Flavor Violation Searches

Two of these experiments, E865 and E871, made use of the tremendous kaon flux available at the AGS to push the sensitivity of searches for physics beyond the SM (BSM), in particular, to search for lepton flavor violating decays. These experiments have, or will soon, reach single event sensitivities of $\sim 10^{-12}$ and have excluded or severely limited many possible extensions to the SM. A summary of limits from these searches for BSM physics is provided in Table 1. The E871 experiment is finished with all data analysis, but new results on $K^+ \to \pi^+ \mu^+ e^-$ and other modes are expected from E865 in the near future.

Table 1
Searches for decays not allowed in the standard model

Decay Mode	BR	Reference
$K^\circ_L \to \mu e$	$< 4.7 \times 10^{-12}$	E871-98 [6]
$K^+ \to \pi^+ \mu^+ e^-$	$< 2.8 \times 10^{-11}$	E865-00 [7]
$K^+ \to \pi^+ X^\circ$	$< 5.9 \times 10^{-11}$	E787-02 [8]
$K^+ \to \pi^- \mu^+ e^+$	$< 5.0 \times 10^{-10}$	E865-00 [9]
$K^+ \to \pi^+ \mu^- e^+$	$< 5.2 \times 10^{-10}$	E865-00 [9]
$K^+ \to \pi^- e^+ e^+$	$< 6.4 \times 10^{-10}$	E865-00 [9]
$K^+ \to \pi^- \mu^+ \mu^+$	$< 3.0 \times 10^{-9}$	E865-00 [9]
$K^+ \to \pi^+ \gamma$	$< 3.6 \times 10^{-7}$	E787-02 [10]

2.2. Chiral Perturbation Theory

A number of other modes have been observed for the first time, or with significantly larger statistics than was previously available. These modes are of interest as a testing ground for Chiral Perturbation Theory (ChPT). A summary of these measurements is provided in Table 2.

A byproduct of the E871 search for $K^\circ_L \to \mu e$, and a demonstration of the capabilities of the experiment is the observation of the $K^\circ_L \to e^+ e^-$ decay, with the smallest BR ever measured for an elementary particle decay. Along with $K^\circ_L \to e^+ e^-$, a very high statistics measurement of the until recently considered 'rare' decay $K^\circ_L \to \mu^+ \mu^-$ was made. This mode is very interesting due to its historical significance, and to the fact that the short distance component of this decay is sensitive to ρ or $Re\lambda_t$. The dominant contribution to this decay is from two real photons and is well known from QED and the measured value of B($K^\circ_L \to \gamma\gamma$). It may be possible, with additional theoretical work [21] and/or new data (for example, from $K^\circ_L \to \mu^+ \mu^- e^+ e^-$ from KTeV at FNAL) to determine the long distance dispersive contribution to this mode, although there is some controversy on this point [22]. If all long distance contributions can be calculated, this measurement will be able to provide an independent constraint on λ_t. A summary of the $K^\circ_L \to \ell^+ \ell^-$ modes can be found in Table 2.

2.3. CKM Matrix and CP-violation

The third experiment, E787, was designed to search for the decay $K^+ \to \pi^+ \nu\overline{\nu}$. This experiment made use of the tremendous flux of low energy kaons to measure this very rare mode (branching ratio $\sim 10^{-10}$) with only one detectable particle in the final state. A summary of $\pi^+ \nu\overline{\nu}$ results is provided in Table 3.

The first $K^+ \to \pi^+ \nu\overline{\nu}$ signal was observed in the 1995 data sample of the E787 experiment [24]. No new events were seen in the data sample from 1996–97 [25], and with a background of 0.08 ± 0.02 events and a signal of one event a branching ratio of $1.5^{+3.4}_{-1.2} \times 10^{-10}$ was measured. That event was in fact in a very clean region of the signal box with a standard model signal to background ratio of 35. An analysis of the final E787 data sample from the last run in 1998 has recently been reported [8]. With a measured background of $0.066^{+0.044}_{-0.025}$, one new event was observed. The final plot of range vs. energy from the combined E787 1995–98 data sample for events passing all other cuts is shown in Figure 1. The branching ratio, as determined from these two events is

Table 2
Modes of interest to Chiral Perturbation theory

Decay Mode	Branching Ratio	Events	Experiment	Ref
$K_L^\circ \to \mu^+\mu^-$	$(7.24 \pm 0.17) \times 10^{-9}$	6200	E871 (2000)	PRL **84**:1389 [11]
$K_L^\circ \to e^+e^-$	$(8.7^{+5.7}_{-4.1}) \times 10^{-12}$	4	E871 (1998)	PRL **81**:4309 [12]
$K^+ \to \pi^+\gamma\gamma$	$(6.0 \pm 1.5 \pm .7) \times 10^{-7}$	26	E787 (1997)	PRL **79**:4079 [13]
$K^+ \to \pi^+e^+e^-$	$(2.94 \pm .05 \pm .13) \times 10^{-7}$	10,300	E865 (1999)	PRL **83**:4482 [14]
$K^+ \to \pi^+\mu^+\mu^-$	$(5.0 \pm .4 \pm .6) \times 10^{-8}$	200	E787 (1997)	PRL **79**:4756 [15]
$K^+ \to \pi^+\mu^+\mu^-$	$(9.22 \pm .60 \pm .49) \times 10^{-8}$	430	E865 (2000)	PRL **84**:2580 [16]
$K^+ \to \pi^+\pi^\circ\gamma$ (DE)	$(4.72 \pm .77 \pm .28) \times 10^{-6}$	360	E787 (2000)	PRL **85**:4856 [17]
$K^+ \to \pi^+\pi^-e^+\nu_e$	$(4.11 \pm .01 \pm .11) \times 10^{-5}$	388,270	E865 (2001)	PRL **87**:221801 [18]
$K^+ \to \mu^+\nu_\mu\gamma$ (SD)	$(1.33 \pm .12 \pm .18) \times 10^{-5}$	2588	E787 (2000)	PRL **85**:2256 [19]
$K^+ \to e^+\nu\mu^+\mu^-$	$< 5.0 \times 10^{-7}$	0	E787 (1998)	PR **D58**:012003 [20]

Table 3
Measurements of the CKM Matrix and CP-violation

Decay Mode	Branching Ratio	Events	Experiment	Ref
$K^+ \to \pi^+\nu\overline{\nu}$	$(1.57^{+1.75}_{-0.82}) \times 10^{-10}$	2	E787 (2002)	PRL **88**:041803 [8]
$K_L^\circ \to \pi^\circ\nu\overline{\nu}$ ($\pi^+\nu\overline{\nu}$)	$< 1.7 \times 10^{-9}$	—	E787 (2002)	indirect [8]
$K \to \pi^+\pi^\circ\nu\overline{\nu}$	$< 4.3 \times 10^{-5}$	0	E787 (2001)	PR **D63**:032004 [23]

$1.57^{+1.75}_{-0.82} \times 10^{-10}$. This branching ratio is a factor of two higher than expected in the SM and is higher than allowed by the current limit on B_s mixing. Of course, the uncertainty on the BR measurement is large due to limited statistics and new data from the E949 experiment are eagerly awaited.

The new event found in the 1998 data sample is in a relatively clean region of the accepted signal region: the SM signal to background ratio for this event is 3.6. An event display is shown in Figure 2.

From the 90% CL limits $0.56 \times 10^{-10} < B(K^+ \to \pi^+\nu\overline{\nu}) < 3.9 \times 10^{-10}$ a limit on the branching ratio of the neutral mode can be derived [4]

$$\begin{aligned} B(K_L^\circ \to \pi^\circ\nu\overline{\nu}) &< 4.4 \times B(K^+ \to \pi^+\nu\overline{\nu}) \\ &< 1.7 \times 10^{-9} \quad (90\%\,\mathrm{CL}). \end{aligned}$$

Limits on $|V_{td}|$ and λ_t can be obtained (these are 1-σ limits except for $Im\lambda_t$ which is 90% CL),

$$\begin{aligned} 0.007 < \; & |V_{td}| < 0.030, \\ 2.9 \times 10^{-4} < \; & |\lambda_t| < 1.2 \times 10^{-3}, \\ -0.88 \times 10^{-3} < \; & Re\lambda_t < 1.2 \times 10^{-3}, \\ & Im\lambda_t < 1.1 \times 10^{-3}. \end{aligned}$$

Even with the large statistical error, this new measurement of B($K^+ \to \pi^+\nu\overline{\nu}$) provides a non-trivial contribution to global fits of the CKM parameters [5]. The constraints on λ_t from this result are shown in Figure 3. The constraints from the other golden B modes, $\Delta M_{B_d}/\Delta M_{B_s}$ and $B_d^\circ \to \psi K_S^\circ$ are shown on the same plot. One can immediately see that the allowed region is tightly constrained to a narrow crescent by $K^+ \to \pi^+\nu\overline{\nu}$ and $\Delta M_{B_d}/\Delta M_{B_s}$. New data from the successor to E787, E949 will make a significant contribution to our knowledge of the CKM parameters.

In addition, E787 has searched for the decay $K^+ \to \pi^+\nu\overline{\nu}$ in the pion kinematic region below the $K^+ \to \pi^+\pi^\circ$ ($K_{\pi 2}$) peak [26]. This region contains more of the $K^+ \to \pi^+\nu\overline{\nu}$ phase space, but is complicated by a significant background from $K^+ \to \pi^+\pi^\circ$ decays with the π^+ scattering in the scintillating fiber target and down-shifting its kinematics into the search region. The data from the 1996 run of E787 has been analyzed (~20% of the entire E787 data sample). One event was observed in the search region, consistent with the background estimate of 0.73 ± 0.18. This implies an upper limit on B($K^+ \to \pi^+\nu\overline{\nu}$)

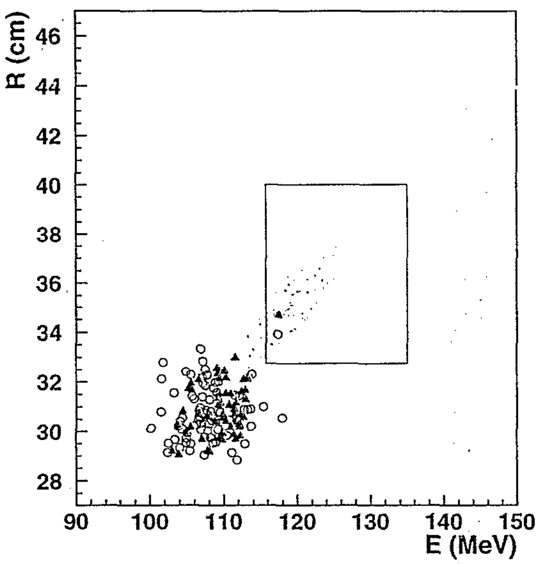

Figure 1. Final E787 plot of range vs. energy for events passing all other cuts. The circles are for 1998 data and the triangles are for 1995–97 data. Two clean $K^+ \to \pi^+ \nu\bar{\nu}$ events are seen in the box. The remaining events are $K^+ \to \pi^+ \pi^\circ$ background. A $K^+ \to \pi^+ \nu\bar{\nu}$ Monte Carlo sample (dots) is overlayed on the data.

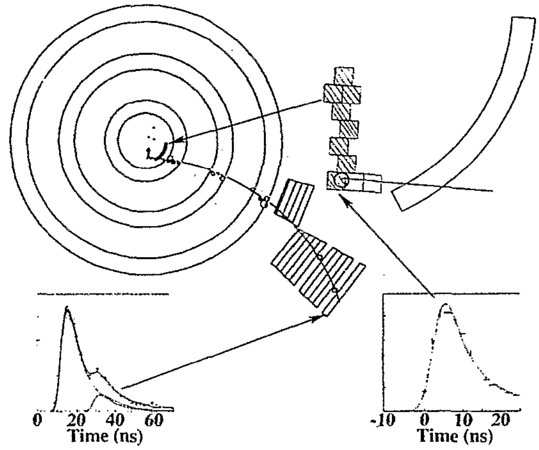

Figure 2. Event display for the second $K^+ \to \pi^+ \nu\bar{\nu}$ event, discovered in the E787 data sample from 1998. The upper left shows an end view of the detector. The top right shows an expanded view of the target region, with a view of the digitized pulse in the fiber where the kaon stopped in the lower right. The lower left shows the digitized $\pi^+ \longrightarrow \mu^+$ decay signal in the scintillator where the pion stopped.

$< 4.2 \times 10^{-9}$ (90% C.L.), and is consistent with the 2 events observed above the $K_{\pi 2}$ peak and the SM spectrum. Some additional reduction of the background levels in the remaining E787 data may be possible, but the major focus will shift to the new E949 experiment, which has significantly enhanced photon veto capabilities that will further suppress this background. In addition, the next experiment after E949, CKM at FNAL, will be essentially free of this background since there is no stopping target.

3. CURRENT PROGRAM

The current high energy physics program at BNL consists of one experiment: E949 — A measurement of the branching ratio $B(K^+ \to \pi^+ \nu\bar{\nu})$. This is the first of the AGS-2000 experiments to be approved and is to be funded by DOE for 6000 hours of running beginning in 2002. Unfortunately, the FY02 run will fall substantially short of the planned running time, so the expectation is that E949 will need to run beyond FY03.

3.1. E949

E949 is an upgraded version of the E787 experiment, planning to capitalize on the full AGS beam to collect $K^+ \to \pi^+ \nu\bar{\nu}$ data at 14 times the rate of the E787 run in 1995. The new detector has substantially upgraded photon veto capabilities, enhanced tracking, triggering, monitoring, and DAQ capability, and will run at a higher AGS duty factor and a lower kaon momentum (with an increased fraction of useful, stopped kaons). It has been designed to reach a sensitivity of at least 5 times beyond E787 and observe of 5–10 SM events. The background level for E949 measurement of $B(K^+ \to \pi^+ \nu\bar{\nu})$ above the $K_{\pi 2}$ peak is reliably projected from E787 data to be $\sim$10%

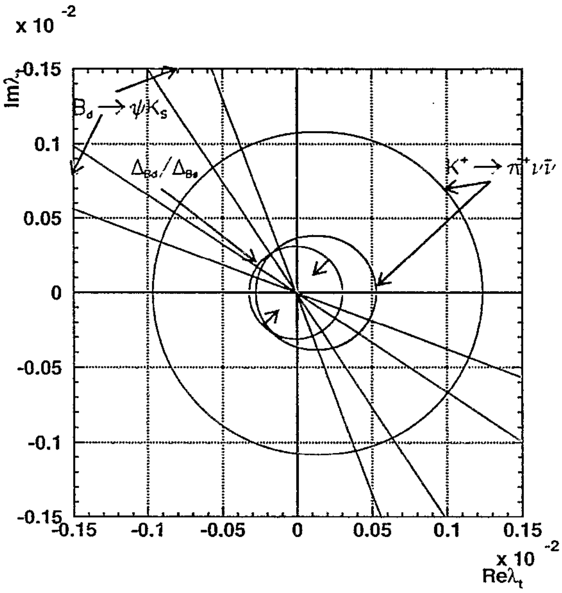

Figure 3. Constraints on λ_t from $\mathrm{B}(K^+ \to \pi^+ \nu\overline{\nu})$, $\Delta M_{B_d}/\Delta M_{B_s}$ and $B_d^\circ \to \psi K_S^\circ$. The experimental measurements for $\Delta M_{B_d}/\Delta M_{B_s}$ and $K^+ \to \pi^+ \nu\overline{\nu}$ are 90% CL limits and for $\Delta M_{B_d}/\Delta M_{B_s}$ is a 95% CL limit. The theoretical uncertainties in all of these modes are small. A measurement of $K_L^\circ \to \pi^\circ \nu\overline{\nu}$ will provide a constraint on $Im\lambda_t$.

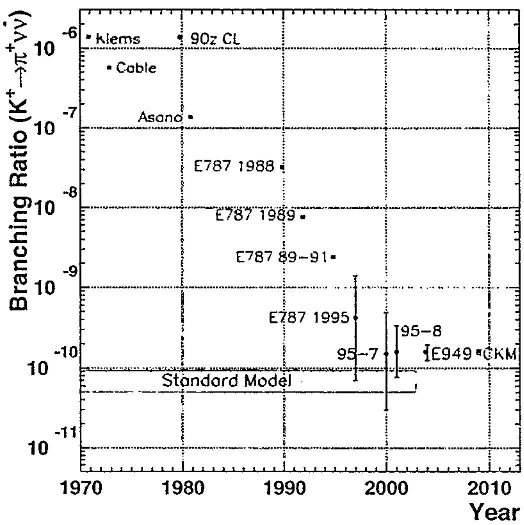

Figure 4. History of the search for $K^+ \to \pi^+ \nu\overline{\nu}$. The squares represent 90% CL limits, the dark circles are the E787 observation of $K^+ \to \pi^+ \nu\overline{\nu}$, and the projections of the current BR to the proposed E949 and CKM sensitivities. The prediction from the standard model is expected to narrow considerably once B_s°—$\overline{B_s^\circ}$ mixing has been observed.

of the Standard Model signal.

E949 should see up to 10 SM events (or 20 events at the branching ratio measured by E787) within the next couple of years. This is an exciting opportunity to make a significant contribution to quark mixing and CP-violation that should be fully exploited. A history of the search for $K^+ \to \pi^+ \nu\overline{\nu}$ is shown in Figure 4. The next step towards a precision measurement of $\mathrm{B}(K^+ \to \pi^+ \nu\overline{\nu})$ will be the CKM experiment at FNAL. CKM has been given scientific (Stage-1) approval by FNAL and could be running by 2007. CKM plans to use a novel technique for $K^+ \to \pi^+ \nu\overline{\nu}$: a decay in flight experiment, with redundant kinematic constraints from a reasonably conventional momentum spectrometer and a novel velocity spectrometer based on RICH counters. CKM expects to observe 100 SM signal events in a two year run, using Main Injector pulses not needed by the Tevatron. CKM will require less than 20% of the flux from the Main Injector, but will require a slow extracted spill of ~1 second. Figure 4 shows a projected measurement of $\mathrm{B}(K^+ \to \pi^+ \nu\overline{\nu})$ from CKM, assuming the current branching ratio.

4. FUTURE PLANS

Other HEP experiments that are under consideration to run at the AGS include additional running for measurement of g-2 of the muon, a search for muon to electron conversion (MECO) and a search for and measurement of the $K_L^\circ \to \pi^\circ \nu\overline{\nu}$ branching ratio (KOPIO). The

National Science Board of the National Science Foundation (NSF) has has approved the construction of the two new large experiments: K0PI0 and MECO, as components of the Rare Symmetry Violation Proposal (RSVP). RSVP is planned to be one of the next Major Research Equipment construction projects at the NSF.

4.1. K0PI0

The KOPIO experiment is designed to discover the $K_L^\circ \to \pi^\circ \nu\overline{\nu}$ decay and measure its branching ratio to ~20%. KOPIO will make use of a time-of-flight technique to measure the momentum of the K_L and will operate at a large targeting angle to improve the p_K resolution and soften the neutron spectrum to reduce π° hadroproduction. KOPIO will have a substantial photon veto system and make the same sort of background measurements as E787, directly from the data, with two independent tools for attacking the major background, $K_L^\circ \to \pi^\circ\pi^\circ$, through both kinematics and photon veto. K0PI0 expects to observe 50 SM events, with a background of 50%. This will allow a determination of $Im\lambda_t$ to 10%. K0PI0 is expected to start data collection in ~2006.

5. CONCLUSION

The next decade will be an exciting time for improved understanding of CP-violation and quark mixing. It is quite likely that precise measurements of all four "Golden Modes" will be made: $B_d^\circ \to \psi K_S^\circ$ at the B-factories, $\Delta M_{B_d}/\Delta M_{B_s}$ most likely at the Tevatron, and $K \to \pi\nu\overline{\nu}$ at BNL, KEK and FNAL. These measurements will allow a precise determination of CKM parameters and provide a critical test of the SM picture of CP-violation.

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